Determining the mass of the compact object xte j1652-453 from SWIFT observations

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Abstract: Through the X-ray data from an outburst of the compact object xte j1652-453 in an X-ray binary provided by the Swift telescope, it is intended to put constraints on the mass of that object. And this way determine whether that object can be a black-hole candidate or a neutron star. The data that will be used to do this project was collected by Swift telescope between 2009-07-03 and 2012-06-24. Determining the temperature of the accretion disk it is deduced that xte j1652-453 probably corresponds to a neutron star and some calculations about the mass with distance and inclination also point in this direction. So, the results obtained indicate that the object is a neutron star instead of a black hole.

I. INTRODUCTION

A. Preliminar Concepts

By compact objects we refer to massive high density stars or bodies, mainly white dwarves, neutron stars and black holes. The origin of compact objects is the final stage of stellar evolution, for which they are usually called stellar remnants. The mass of the star from which it comes heavily determines which type of compact object it will be.

Black holes are the most dense type of compact object. A black hole is a zone in space that general relativity predicts, nothing can escape, not even light. Around a black hole, a surface called event horizon delimits a region of space where events on the outside cannot be affected by events on the inside.

A kind of systems that will be important in this project are binary systems. They are systems of two stars orbiting each other. The ones considered in this projct will consist on a compact object and another normal star, called secondary star. In this kind of system, usually, the secondary star transfers matter to the more massive compact object. In this way, an accretion disk is created. The accretion disk is usually the X-ray brightest part of the binary system. The Roche lobe is a concept related with binary systems, it is the region of space in a binary system in which the matter of the secondary star is bound to it as well as to the compact object. If some part of the secondary star reaches outside this region, this matter will no longer be bound to the gravitational potential of the star and will fall to the compact object, creating the accretion disk.

Another important concept is the Eddington limit. Usually referred to as Eddington Luminosity, it is the maximum luminosity a star (or any other body) can emit. This limitation comes from the confrontation of the gravitational force and the radiation pressure, which act in opposite directions. When a star exceeds the Eddington limit the radiation pressure on the outmost layers of the star will overcome the gravity force, ejecting a very intense stellar wind.

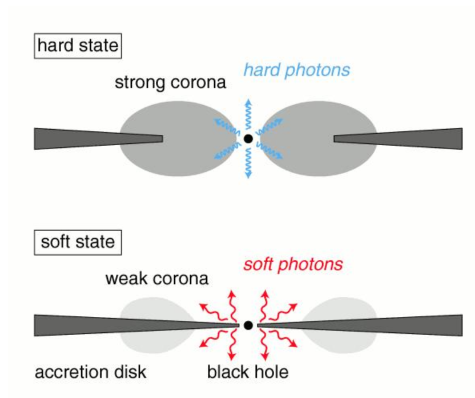

Figure 1: This figure illustrate the difference between soft state and hard state emission. This image was found in [2].

Black hole candidates, and X-ray binaries in general, are observed in different spectral states. The definition of the different states is made in term of their spectral energy. It is said that the system is in hard state, when most of their power is emmited in high frequencies and an exponential cut-off is observed at about 100 keV. On the other hand, the system will be in soft state when most of the energy comes from a thermal component, so from low energy photons. Generally during the outbursts (that is when the data used in this project are collected) this is the state observed.

In the soft state the accretion disk inner radius is not much larger than the compact object radius, that means that some matter of the accreation disk is really close to the compact object. So, the density and the velocity of this matter are really high, so the temperature increases. The temperature arrives at such high levels that starts to emit in X-ray, but not at hard X-ray. The hard X-ray emission comes from a hot and low-density corona that is also present in soft state. But since the soft state has a highly luminous soft X-ray emission, the hard emission does not contribute significantly to the spectrum.

The information about soft state was obtained from [1, 2] and [3].

B. Swift project

The information of this section is extracted mostly from [4], but also from [5–8].

Since the Earth's atmosphere is opaque to UV, X-rays, and gamma rays, it would be difficult to make observations of the universe in these wavebands with a ground telescope. In this fact lies the importance of having the equipment to make these observations on a satellite orbiting the Earth.

Swift is a multi-wavelength observatory dedicated to the study of gamma ray bursts (GRB). It is a NASA mission with international participation, a satellite equiped with three instruments that work together to provide information about gamma-ray and X-ray bursts, by observing GRB and their afterglows in the gamma ray, X-ray, ultraviolet and optical wavebands.

Gamma-ray bursts are the most powerful explosions in the Universe and it is the main aim of Swift to study them. However, this project focuses on X-ray binaries.

The Swift telescope consists in three instruments, which are the Burst Alert Telescope (BAT), the X-ray Telescope, and the UV/Optical Telescope.

The X-ray Telescope (XRT) allows to measure the position, the spectrum and the brightness of GRB. It has a high sensitivity of an order of magnitude of $10^{-21}\,\mathrm{Jcm^{-2}s^{-1}}$ and covers a wide range of magnitude in flux. It also has a waveband from 0.2 to 10 keV.

The data produced by the X-Ray Telescope that will be used in this project are: light curves and energy spectrum. All the Swift data products are available to the public on the internet right after their processing.

II. SWIFT DATA OF THE X-RAY BINARY XTE J1642-453

The data collected by Swift is presented in different ways, by means of the different data products. The products used for this project are event list, light-curve, image and spectrum. In this section a brief explanation about this Data Products will be done.

There are different levels of data products. Depending on how much the data is processed, the product obtained will be classified at its corresponding processing level. Standard products are classified at level 3, and most of the data used in this project is from this kind, but it is also used a product from level 1, that means less processed, which is the event list.

The event list basically contains all the information about the incident photons to the detector. It contains the information of how many photons hit the detector, at which time they arrive, with which energy, etc. This data must be filtered through different methods to obtain reliable data.

The remaining products used in this project, which are described below, are all level 3 products.

The light curve shows the observed radiation flux as a function of time. There are different kinds of light curves. The whole light curve represents all the observations along time binning the data of different observations. For instance the lightcurve obtained from data products is shown in figure 2, but it is not the lightcurve directly obtained from Swift. It has been processed to rescale the time axis and set it in days, since the original time was given in seconds since 2001.0 UTC (the time used in the Swift project). In order to do this the clean data from the observations must be obtained. Lightcurve data is obtained from [9] and the time has been converted by means of [10].

Another product that can be obtained is the image. It is an image of the space area in wich the object has been observed. It is not a real optical image but an image obtained by means of processing the data collected. Images are produced in gif and FITS format. The image of xte j1652-453 is shown in figure 3.

The spectrum shows the distribution of energy in the frequency domain of an observation. There are many options suitable for different aims. It is possible to define the time range in which the data is more interesting, or the range of counts or energy that must be avoided. But the spectrum used in this project will be obtained by means of processing

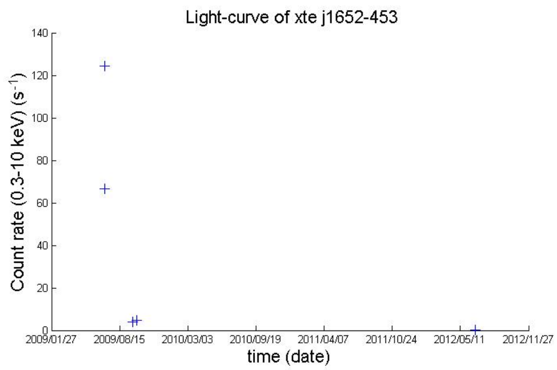

Figure 2: This figure shows the lightcurve of xte j1652-453 obtained from Swift data products.

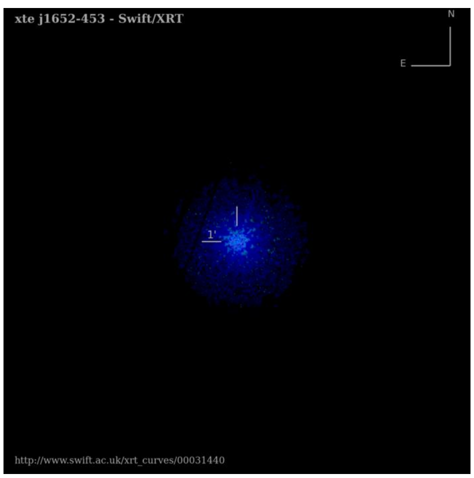

Figure 3: This figure shows the image of the xte j1652-453 obtained from Swift data products.

the data of the event list.

A. X-ray data reduction and analysis software

First of all the data of one observation must be selected, therefore the clean data (the event list) of all these observation will be downloaded and processed. The observation that will be selected is going to be the one with more information available, that means the most energetic one. Moreover, if the brightest observation is selected will be appropiate to compare the data with the theoretical maximum (Eddington limit). In the lightcurve (figure 2) are ploted the fluxes emitted during different observations. The brightest observation is selected, and the day and the hour of the observation is obtained converting the Swift time with [10]. The data used in this project was collected in 2009-07-03 at 13:20:01. After doing that, the clean data is downloaded from [11].

To process this event list HEASOFT software will be used, downloaded from [12]. First of all we must run pipeline to the data, in aim to obtain the files that can be analized. After that, if we look at the spectrum (level 3) we can appreciate that the data had suffered pile-up. Pile-up consists on groups of photons being detected as a single one with higher energy. This phenomena is produced when the count rate is higher than the detector can measure. This produces an error on the spectrum, making it to have a flattened curve at the brightest energies and a wider tail on the high energies. In order to correct this, it is possible to ignore the photon counts of the most intense central regions of the Point Spread Function and take into account only regions with lower count rates.

To be sure that pile-up is happening we adjust a king curve to the data of counts in function of the angle (angle centered in the center of the image), and at the points in which the curve is above de data, pile-up is happening. By this way the pixels that are suffering pile-up are obtained and must be avoided.

For the task of avoiding the pixels with pile-up, an annulus region is defined using an image of the object, by means of XSELECT, one of the programs from the HEASOFT package. This region contains the brightest part of the data, except for the ones that are suffering pile-up. Then, when plotting the count rate, only the photon counts from this regions will be taken into account.

It is also possible to define a region as background. In this way, if some radiation arrives at the telescope from undesired sources, the data can be corrected, using the background information, to avoid the effect of that radiation.

In order to plot the count rate as a function of the photon energy, it is needed to know the relation between the SWIFT energy channels and their energy values. This information is given by the response matrices which depend on the instruments and the observation conditions. The corresponding files can be downloaded like the other SWIFT data. Using the grppha task from the HEASOFT package, these files are used to produce a new file that combines the response matrices and the observation data.

Finally, when all corrections are done and reliable data obtained, the analysis of the data can start. Using XSPEC a model is fit to the data. The XSPEC software, which is part of the HEASOFT package, is used to plot the corrected spectrum and to fit models to the data. With the information of the parameters

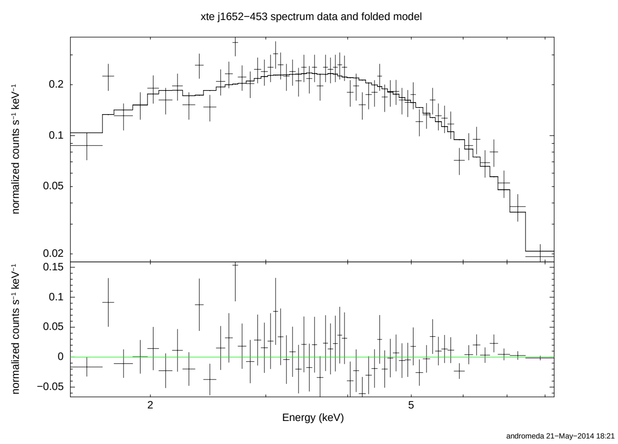

Figure 4: This figure shows the spectrum and the fitted model of the xte j1652-453 obtained after all the processing.

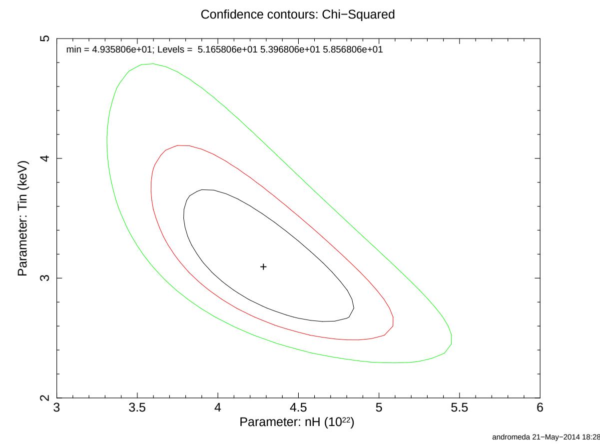

Figure 5: This figure shows confidence contours of a Chisquare likelihood function exploring the parameters T_{in} and Hn.

of the best fit model then it is possible to estimate roughly the mass of the compact object.

The basic model used corresponds to the black-body emission of a disk. Its parameters are the radius of the disk and its temperature. Also, a hydrogen absorption component is added to the model, which adds another parameter: the hydrogen column density. The hydrogen column is the number of hydrogen atoms per square centimeter between the object and the observing instruments. After the model has been selected, the XSPEC software identifies which values of the parameters make the model fit best the data. With this process the best fitting values are found along with the corresponding confidence intervals.

The spectrum and the fitted model obtained with the data used in this project are shown in figure 4.

For the fitting of the model the program adjusts some parameters trying to minimize a chisquare likelihood function. The parameters obtained in this case are:

$$\begin{aligned} \text{nH} &= 4.293 \cdot 10^{22}\,\text{cm}^{-2} \\ T_{in} &= 3.08\,\text{KeV} \\ \text{Norm} &= 0.380 \end{aligned}$$

But this parameters are approximated, so it is necessary to know how reliable they are. It is necessary to know what is the error of this parameters, at least the error produced by statistical issues. To do so, confidence contours for pairs of parameters are plotted, one of them is shown in figure 5. From this information it is right to assure, with tolerance about one sigma, that $\text{nH} \in \left[3.8\,\text{cm}^{-2}, 4.85\,\text{cm}^{-}2\right]$, $T_{in} \in [2.6\,\text{KeV}, 3.7\,\text{KeV}]$ and Norm $\in [0.2, 0.65]$.

The conclusions obtained with this values are explained in the next section.

III. CONCLUSIONS

The first conclusion that can be obtained from the results above, without doing any calculations is that probably the object xte j1652-453 is a neutron star (and not a black hole). Because the T_{in} obtained is higher than 1 keV, that means that probably the accretion disk is completely observed, since the inner part of the accreation disk is the hottest. The observable part of the accretion disk of a black hole does not exceed temperatures of 1 keV. So, it can not be a black hole because the hottest part of the accretion disk would be inside the event horizon, so it could not be observed.

In the following lines the results obtained previusly are analysed. The following equations will be used:

$$L_{edd} = 3.2 \cdot 10^4 \frac{M}{M_\odot} L_\odot \tag{1}$$

$$\text{Norm} = \left(\frac{R_{in}/\text{km}}{D/10\text{kpc}}\right)^2 cos\theta \tag{2}$$

$$L = 4\pi\sigma R_{in}^2 T_{in}^4 \tag{3}$$

Where L_{edd} is the Eddington limit, $L_{\odot} = 3.846 \cdot 10^{26}\,\mathrm{W}$ and $M_{\odot}$ are the luminosity and the mass of the sun respectively. Norm (Normalization) is the parameter obtained above, R_{in} is the accretion disk interior radius ($\approx$ radius of the compact object), D is the distance to the object (kpc stands for kiloparsec) and θ is the angle at which the accretion disk is observed. Finally σ is the Stefan-Boltzmann constant equal to $5.67 \cdot 10^{-2}\,\mathrm{Wkm^{-2}K^{-4}}$ and T_{in} is the inner temperature of the accreation disk (or its energy equivalent). K_B is the Boltzmann constant with a value of $8.6173 \cdot 10^{-8}\,\mathrm{keV/K}$. From the equation (2) $R_{in}/\mathrm{km} = \sqrt{\mathrm{norm}/\cos\theta \cdot (D/10\,\mathrm{kpc})}$ is obtained, and from (1) $M = L/L_{\odot} \cdot M_{\odot} \frac{1}{3.2 \cdot 10^4}$. So, it is easy to obtain:

$$M = \frac{4\pi\sigma}{L_{\odot}} \mathrm{Norm} \left(\frac{D}{10\,\mathrm{kpc}} \right)^2 \frac{1}{\cos\theta} \frac{T_{in}^4}{K_B^4} \frac{1}{3.2 \cdot 10^4} M_{\odot}$$

By substitution of the known variable values the following equation is obtained:

$$M = 0.0359 \cdot (D/10\,\mathrm{kpc})^2 \frac{1}{\cos\theta} M_{\odot} \qquad (4)$$

So, assuming $D/10\mathrm{kpc} \simeq 1$ (which means the object is at a distance of 10 kpc), $\cos\theta \leq 1$ and calculating:

$$M \gtrapprox 0.04 M_{\odot}$$

This result is clearly not possible since a neutron star has a mass at least of about $1.5 M_{\odot}$, see [14]. So the argument could be done backwards. Let's assume $M \approx 1.5 M_{\odot}$. So, by means of the equation 4 can be obtained the following result:

$$(D/10\,\mathrm{kpc})^2 \cdot \frac{1}{\cos\theta} \approx 41.8$$

So if the distance of the object is assumed to be $D \approx 1\,\mathrm{kpc}$ the angle must be greater than $\theta \approx 89.99$, that means that the accretion disk is completely parallel to our point of view. On the other hand, if the distance is assumed to be $D \approx 10\,\mathrm{kpc}$, which is a usual value for this type of objects, then $\theta \approx 88.63$. And finally, if a distance of about $D \approx 35\,\mathrm{kpc}$ is assumed, $\theta \approx 73.0$ that is more believable than the other results. It is not possible to assume a larger distance, because 35 kpc is approximately the diameter of the galaxy. If it were front-on it would have to be at a distance of 64 kpc. The data of galaxy sizes has been obtained from [13].

So all the results indicate that xte j1652-453 is a neutron star and that is at least as far as the opposite point of the galaxy. There is also the possibility that the object is from a satellite galaxy of the milky way.

[1] Karttunen, H. et al. *Fundamental Astronomy 5th Edition*. Springer-Verlag Berlin Heidelberg, 2007.

[2] http://www.mpa-garching.mpg.de/mpa/research/current_research/hl2005-2/hl2005-2-en.html

[3] http://www.mpe.mpg.de/~am/mcd.html

[4] Gehrels et al. "The Swift Gamma-Ray Burts Mission". *The Astrophysical Journal*, 611:1005–1020, 2004 August 20.

[5] http://swift.gsfc.nasa.gov/about_swift/xrt_desc.html

[6] http://swift.gsfc.nasa.gov/about_swift/

[7] http://swift.gsfc.nasa.gov/

[8] Burrows, D., Kennea, J., Nousek, A., Gehrels, N. "The Swift Target of Opportunity Program". http://maxi.riken.jp/FirstYear/proceedings/pdf/Burrows_David_N.-bin-20110209234806.pdf

[9] http://www.swift.ac.uk/user_objects/

[10] http://heasarc.gsfc.nasa.gov/cgi-bin/Tools/xTime/xTime.pl

[11] http://heasarc.gsfc.nasa.gov/cgi-bin/W3Browse/swift.pl

[12] http://heasarc.nasa.gov/lheasoft/download.html

[13] http://en.wikipedia.org/wiki/List_of_nearest_galaxies

[14] http://stellarcollapse.org/nsmasses

[15] http://www.swift.ac.uk/user_objects/docs.php#obform

[16] http://www.swift.ac.uk/analysis/xrt/xrtpipeline.php